OVERVIEW OF NASA SPACE CRYOCOOLER PROGRAMS

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ABSTRACT

Mechanical cryocoolers represent a significant enabling technology for NASA's Earth and Space Science Enterprises, as well as augmenting existing capabilities in space exploration. An overview is presented of ongoing efforts at the Goddard Space Flight Center and the Jet Propulsion Laboratory in support of current flight projects, near-term flight instruments, and long-term technology development.

INTRODUCTION

NASA programs in Earth and space science observe a wide range of phenomena, from crop dynamics to stellar birth. Many of the instruments require cryogenic refrigeration to improve dynamic range, extend wavelength coverage, and enable use of specific detector technologies. Over the last two decades, NASA has supported cryocooler technology development in support of these projects, and has also taken advantage of coolers developed under Defense Department and commercial funding [1]. As coolers have increased in capability, and as the perception of risk associated with a cooler has declined, NASA programs have become more likely to baseline a cryocooler in place of an expendable cryogen system. The largest utilization is currently in instruments operating at medium to high cryogenic temperatures, reflecting the relative maturity of the technology at these temperatures. To date, almost all of these are in Earth Science instruments.

CURRENT TECHNOLOGY

Coolers from a number of sources are either on-orbit or scheduled for launch in the near future. Most are based at least partially on the Oxford cooler technology that first flew on the ISAMS instrument in 1991. This type of cooler has shown the potential for multi-year lifetime in the lab, and has garnered enough confidence on the part of NASA instrument managers that it is not seen as a major risk factor in an instrument.

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Coolers for Terra Spacecraft

The Terra spacecraft, launched in December 1999 with a total of five instruments, is the first spacecraft in NASA's Earth Observing System. It carries a total of four cryocoolers. The ASTER instrument's Short-Wave Infrared subsystem uses a cooler built by Mitsubishi Electric to cool a PtSi CCD array to 77K, and the Thermal Infrared subsystem uses a cooler built by Fujitsu Limited to cool a HgCdTe array to 80K. The MOPITT instrument uses two back-to-back 50-80K BAe/Matra Marconi coolers to cool two separate detector arrays to 85-90K. One of the two MOPITT coolers suffered a failure somewhere in the displacer electronics or mechanism in May 2001, and is currently in a troubleshooting mode.

Hyperion Cryocooler

Hyperion is one of three instruments on the EO-1 spacecraft. The mission is considered a technology demonstration for future generations of instruments in the Landsat program. The intent is to show compatibility with existing Landsat data sets for resource usage, while providing a wealth of additional spectral data for Earth science applications. A follow-on to TRW's Hyperspectral Imager on NASA's failed Lewis spacecraft, Hyperion covers the band from 0.9 – 2.5μm, using a TRW mini pulse tube cooler [2] to refrigerate a HgCdTe focal plane to 110K.

The cooler has performed well throughout the mission, but suffered a failure in the position-control loop on the balancer in January 2001. It was re-configured to run at nominal stroke without position control, and has been operating nominally since February.

AIRS Cryocooler Development

Another NASA instrument with TRW coolers scheduled for launch in the very near term is the Atmospheric Infrared Sounder (AIRS) instrument. This instrument measures atmospheric air temperature using a HgCdTe focal plane operating at 58K and is scheduled to be flown on NASA's Earth Observing System Aqua platform in the December 2001 timeframe; it was designed and built under JPL contract by Lockheed Martin Infrared Imaging Systems, Inc. (now BAE Systems IR Imaging Systems) of Lexington, MA. The cryocooler development effort was a highly collaborative effort involving cryocooler development at TRW, and extensive cryocooler testing at JPL and Lockheed Martin [3]. In the first phases of the AIRS cooler effort, contracts were awarded to BAe (now MMS) and Lockheed-Lucas for the development-testing of advanced second-generation Stirling cryocoolers with the needed capacity, efficiency, and low vibration. These early efforts fostered important design improvements associated with reduced off-state conduction down the cold finger, and high accuracy coldtip temperature regulation via compressor piston stroke control [4,5]. They also illuminated important technical challenges that could be more easily met by the use of an advanced pulse tube expander in place of the Stirling displacer.

In 1994, TRW was awarded the contract to develop and produce the 1.5W-55K flight coolers for the AIRS instrument. The TRW AIRS pulse tube cooler, shown in FIG 1 with its drive electronics, has excellent thermal performance, comparable to the best Stirling coolers, and has a number of features that greatly improve instrument integration. These include reduced mass, size and complexity, increased stiffness, and reduced vibration at the cold head. The AIRS flight pulse tube coolers, delivered to JPL for testing in October 1997, and to the instrument for integration in January 1998, have been extensively characterized and have met all of their key performance goals [6,7].

TES Cooler Development

The second large cryogenic instrument presently under development at JPL is the EOS Tropospheric Emission Spectrometer (TES) instrument. TES is an infrared satellite instru-

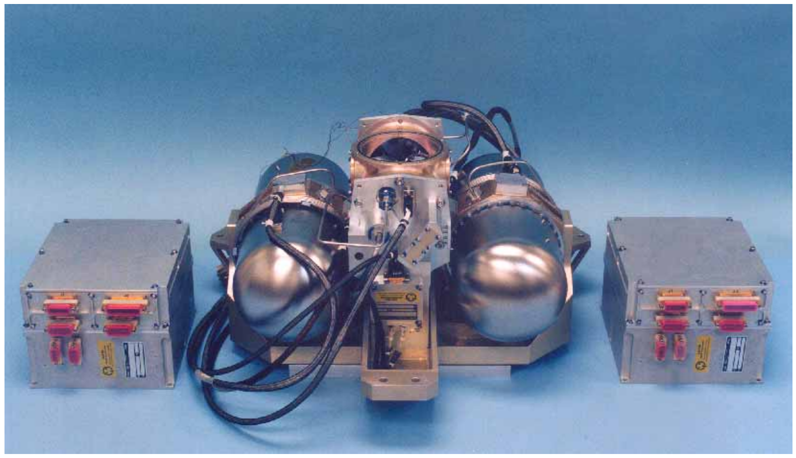

FIGURE 1. The fully redundant AIRS cooler system, with its electronics.

ment designed to measure the state of the earth's troposphere. It is scheduled for launch into polar orbit aboard NASA's third earth observing systems spacecraft (EOS-Aura) in the 2003 timeframe.

TES uses two 57K coolers to cool two separate focal planes to 62 K. The two coolers are identical and are a variant of the TRW AIRS pulse tube cooler, but configured with the pulse tube hard mounted to the compressor. The coolers were fabricated by TRW under contract to JPL, and have been extensively characterized at JPL in preparation for integration into the overall TES instrument later this year [4,5].

IMAS Cooler Development

A third JPL cooler development program was conducted in the 1996-1998 timeframe to provide a next-generation pulse tube cryocooler for advanced instruments needing lightweight, efficient cooling in the 50 to 150K temperature range. The cooler concept was referred to as the Integrated Multispectral Atmospheric Sounder (IMAS) cooler in recognition of the NASA/JPL advanced concept instrument program under which the development took place. This very successful development effort was carried out at TRW and led to a new cooler with comparable thermal performance to the AIRS and TES pulse tube coolers, but with one quarter of the mass and size [8 ,9]. FIGURE 2 contrasts the IMAS cooler with the much larger TES cooler. Subsequent refinement of the IMAS cooler has led to what TRW refers to as its High Efficiency Pulse Tube cooler [10].

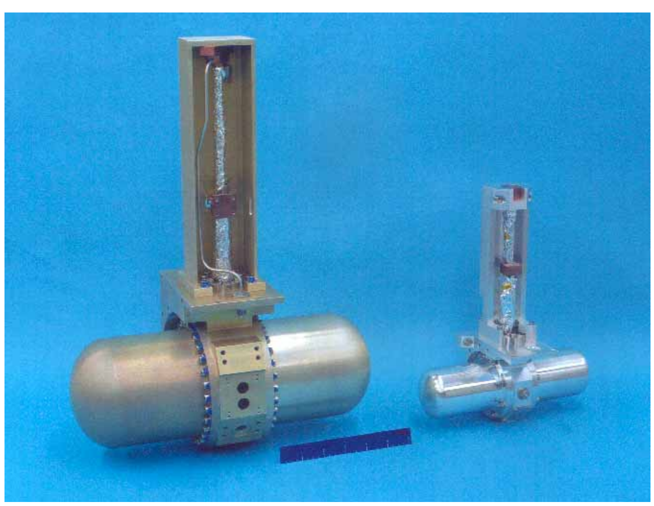

FIGURE 2. TES cooler (left) in comparison to the IMAS cooler (right) and a 6" scale.

A second important part of the IMAS development effort focused on improving the cryocooler electronics. A key issue with nearly all previous coolers is the presence of large amounts of ripple current passed on to the spacecraft's 28 Vdc power bus. On AIRS and TES this ripple current required the introduction of additional special ripple filters between the cryocooler and the spacecraft power system. For IMAS, an active ripple suppression circuit was developed and integrated directly into the cryocooler drive electronics with minimal efficiency and mass penalty [9]. The IMAS drive electronics was subsequently reduced to qualified flight hardware to drive TRW's mini pulse tube cooler for the Hyperion instrument.

HIRDLS Cooler

The High Resolution Dynamics Limb Sounder (HIRDLS) is currently nearing completion for flight on the EOS-Aura spacecraft [11]. This cooler, manufactured by Ball Aerospace under contract to Lockheed / Martin, provides 720mW at 55K for an array covering 21 bands between 6-17µm. It is a single-stage split Stirling cooler, using technology developed under a number of NASA and DoD contracts. It incorporates radial position sensors for establishing and monitoring the clearance seals in the cooler, prior to closeout of the housing. It is similar in design to a two-stage 30K cooler delivered to GSFC in 1997, and life tested to 13,000 hours. The Aura spacecraft is expected to fly in June 2003.

HESSI Gamma-Ray Spectrometer

The High-Energy Solar Spectroscopic Imager (HESSI) uses an array of nine large germanium detectors to observe solar flares from 3keV to 25GeV. A Sunpower M77B Stirling cooler is integrally mounted to the instrument's radiator (see FIG 4) and runs at 65K to maintain the detectors at 75K [12]. Scheduled to be launched in August 2001, the mission is intended to last up to two years on orbit. An unusually large amount of running time has been accumulated on the Sunpower M77B coolers, with three units at or above 8,000 hours of run time prior to first flight. One of these, with 17,000 hours of run time, was in the spacecraft when a test mishap in March 2000 subjected the instrument to vibration inputs greater than 50g. That cooler's performance was degraded [13], and a backup unit, put together from modules of other units in the lab, will eventually be flown in its place.

AMS-2 Charged-Particle Spectrometer

A set of four Sunpower M87 coolers has been baselined to fly on the Alpha Magnetic Spectrometer – 2 (AMS-2) mission in October 2004. The instrument, mounted on the International Space Station, will use a large superconducting magnet assembly in a search for

FIGURE 3. Sunpower M77B Stirling cryocooler integrated into the HESSI radiator structure.

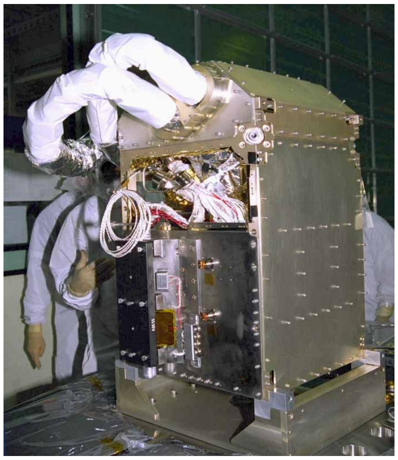

FIGURE 4. The NICMOS Cooling System, integrated for the HST Orbital System Test.

FIGURE 5. The Lockheed Martin mini pulse tube cryocooler with drive electronics.

antimatter nuclei from cosmic sources. The coolers will be used to intercept heat at the outer thermal shield on a 2500 liter helium tank. With the large weight of the superconducting magnets, it is extremely challenging to provide enough thermal isolation to allow a 3-year lifetime, even with the coolers operating at nominal power. The coolers, each capable of 8-9W of heat lift at 85K, will be run at reduced power to provide a total of 20-25W of cooling on the shield.

NICMOS Cooling System

During ground testing prior to launch, the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) instrument for the Hubble Space Telescope was found to have a problem with expansion of the solid nitrogen in its cryogen tank during thermal cycling. This resulted in deformation of the cryogen tank, and a large change in the focal point of the instrument optics mounted on the tank head. After launch in February 1997, the cryogen came up to operating temperature, and expanded further. This caused a thermal short in the dewar, resulting in depletion of the nitrogen in January 1999.

The NICMOS Cooling System, built around a reverse Brayton cooler made by Creare Inc., was flown on a successful demonstration flight in October 1998 [14]. (FIG 4) The system is designed to maintain the instrument's detectors in the range of 75-85K by circulating refrigerated helium gas through the NICMOS dewar's existing liquid helium freeze lines. Bayonet couplings on the NICMOS dewar are used to connect with the gas lines on the cooling system. The system has been reintegrated, and is now scheduled to re-fly in January 2002 to return NICMOS to service.

Technology Developments

To support small instrument applications, Lockheed Martin Advanced Technology Center (ATC) has developed a long-life mini pulse tube cryocooler [16] under a NASA Space Act Agreement. With 500mW of cooling at 65K for 20W of input power, and a cooler mass of 1.3 kg, it is similar in performance to the TRW mini pulse tube cooler. Three have recently been delivered to NASA/GSFC for characterization. As shown in FIG 5, the Lockheed Martin mini pulse tube cooler has been complemented with lightweight electronics (1.6 kg) developed under internal Lockheed funding.

In a parallel effort, Lockheed Martin also teamed with JPL on a gamma-ray cooler program to develop a low-cost, low-noise, high-reliability pulse tube cooler for highly cost-constrained, long-life space missions such as planetary gamma-ray spectroscopy. The specific focus was for relatively low-cost space missions involving one- to two-year lifetimes.

The developed cooler marries two technologies: a low-cost, high-reliability, linear compressor and drive electronics from the 1.75 W tactical Stirling cryocooler of DRS Infrared Technologies, and an 80 K pulse tube developed specifically for the compressor by Lockheed Martin Advanced Technology Center.

The new cooler [15] achieves over 1.6 watts of cooling at 80 K at 23 W/W, and has the advantages of greatly reduced vibration at the coldtip and no life-limiting moving cold elements. Like Lockheed's mini cooler, the pulse tube is a compact U-tube configuration for improved integration; however, it is mounted to the compressor in a split configuration.

In a third effort, Sunpower, under a NASA Small Business contract, has assembled a single-stage pulse tube cooler similar in performance to its M77 Stirling cooler. Under Phase II of their contract, they are working on packaging the cooler for commercial or flight use.

Other Applications

Another notable application for coolers, other than detectors, is in propulsion systems. NASA’s Glenn Research Center and Ames Research Center are studying the use of cryocoolers to enable zero-boiloff storage of cryogenic propellants in space flight systems [17 ,18]. At the Johnson Space Center, the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) project is designing a system that will use high-temperature superconducting coils for plasma containment and acceleration [19].

FUTURE TECHNOLOGY

The largest technology push within NASA right now is in the temperature range of 4-10K. Missions such as the Next Generation Space Telescope and the Terrestrial Planet Finder plan to use infrared detectors operating between 6-8K, typically arsenic-doped silicon arrays, with telescopes of greater than 5m diameter operating at less than 40K. Other missions call for large aperture telescopes operating as low as 4K. Constellation-X plans to use X-ray micro-calorimeters operating at 50mK. NASA has one flight cooler currently in development, and plans for technology development on additional coolers.

Planck Cooler Development

As a precursor to the US low-temperature cryocooler missions, JPL is presently working on the development of a hydrogen sorption cryocooler for the Planck mission of the European Space Agency. The objective of the Planck mission is to produce very high resolution mapping of temperature anisotropy in the cosmic microwave background (CMB) radiation. The Planck spacecraft is scheduled to be launched around 2007 into a deep-space L2 Lagrangian orbit in order to reduce stray infrared radiation from earth, and to permit passive cooling of the telescope and optical system to 50 to 60 K. In addition to the 50 K passive cooling, the two key instruments are using an active cooling system of three cryocoolers to achieve the low temperatures required to measure the CMB.

The Low Frequency Instrument (LFI) will have an array of tuned radio receivers based on High Electron Mobility Transistors (HEMTs) to detect radiation in the range 30-100 GHz. These receivers will be operated at a temperature of about 20 K. The High Frequency Instrument (HFI) will use bolometers operated at 0.1 K for frequencies from 100 GHz to 900 GHz.

JPL is developing and delivering redundant hydrogen sorption cryocoolers to cool the LFI detectors to 18 - 20 K and to precool the RAL 4 K helium J-T that cools the 0.1 K dilution refrigerators in the HFI cooling system. The sorption cryocooler development (FIG 6) builds on the JPL/DoD/NASA Brilliant-Eyes Ten-Kelvin Sorption Cryocooler Experiment (BETSCE) flown in May 1996 [20 ,21]. The JPL Planck sorption cooler began detailed development in the 1998 timeframe and the qualification/flight #1 unit is scheduled for delivery and instrument integration in early 2003, followed by the second flight unit a year later [22 ,23].

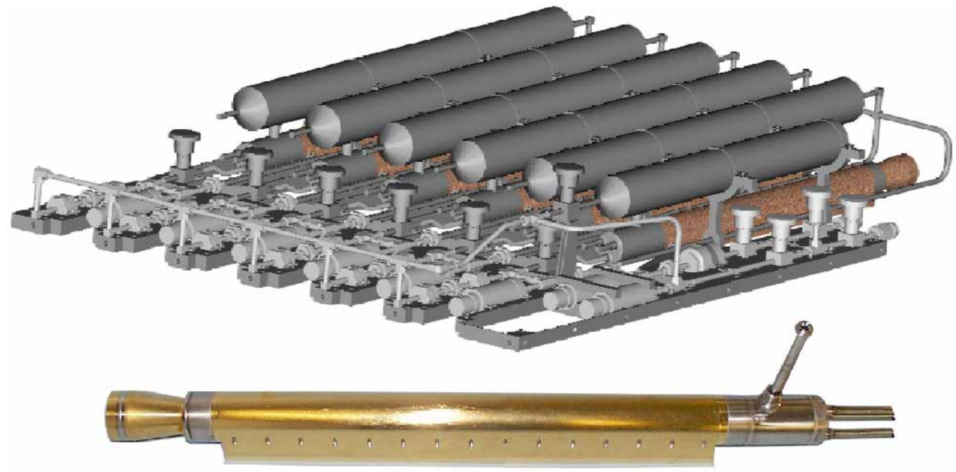

FIGURE 6. 20K Planck sorption compressor system (top) and fabricated compressor element (bottom).

Large Telescope Systems Initiative

In order to meet future needs, NASA is planning the Large Telescope Systems Initiative, beginning in NASA's FY02 or FY03. LTSI will promote development of lightweight deployable optics, low-temperature radiator technology, and sub-10K closed-cycle coolers. The coolers could be Joule-Thomson or reverse-Brayton systems, with additional dilution or adiabatic demagnetization stages for sub-Kelvin requirements.

The initial LTSI cryocooler work will probably focus initially on a 5mW cooler operating at 6K, which would be just about right for interfacing with the Constellation-X sub-K refrigerator, and might be a bit big for TPF's detector refrigerator.

Two coolers are currently funded by NASA for development: a reverse-Brayton cooler being developed by Creare, Inc., and a hydrogen / helium sorption cooler being developed at the Jet Propulsion Laboratory.

The Creare reverse-Brayton cooler underwent final component level testing during early 2001, achieving about 200mW of net refrigeration at 6K. It went into system level testing in June 2001, and a report on results is expected at this conference [24]. This breadboard system is based on compressors built for other projects, with a new low-temperature turbo-alternator.

The JPL 5K sorption cooler concept utilizes a 4 to 6-K helium Joule-Thomson cold-end supplied by a charcoal adsorption compressor heatsunk to 20 K, together with 20-K Stirling, pulse tube, or Planck-like sorption cryocooler to provide the 20 K upper stage cooling [23]. The basic design of the charcoal compressor beds is based on cycling between 80 K for desorption of the helium and 20 K for the adsorption. The compressor beds are paired such that each pair of compressors has its own J-T constriction that can function for flow in either direction — the gas is driven back and forth between the two compressor beds by alternating which bed is hot and which is cold. Charcoal-sorption coolers have the advantages of simplicity, easy scalability, and zero vibration because they have no moving parts near the cold end. The charcoal compressor is also expected be much smaller in mass and volume compared to an ambient temperature mechanical compressor typically used for the 4-K J-T refrigeration stage. A report on results is expected at this conference. [25]

LTSI is also pursuing passive low-temperature cooling, at temperatures usually only reached with cryocoolers or stored cryogens. Both NGST and TPF plan to passively cool their optics to 35K, incorporating sophisticated sunshades and thermal isolation structures to minimize heat input, and incorporating large radiators to maximize heat rejection. This option is made possible by the orbits selected for these missions, well away from the thermally-disruptive presence of the Earth.

SUMMARY

Cryocoolers have finally come into flight usage in NASA science instruments. Flight coolers are available with a wide range of capabilities. NASA-funded technology development is now focusing primarily on 4-10K coolers.

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